# Autonomous VTOL Scalable Logistics Architecture (AVSLA)

Presented by

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## NIAC Annual Fellows Meeting

**NASA - Ames Research Center**

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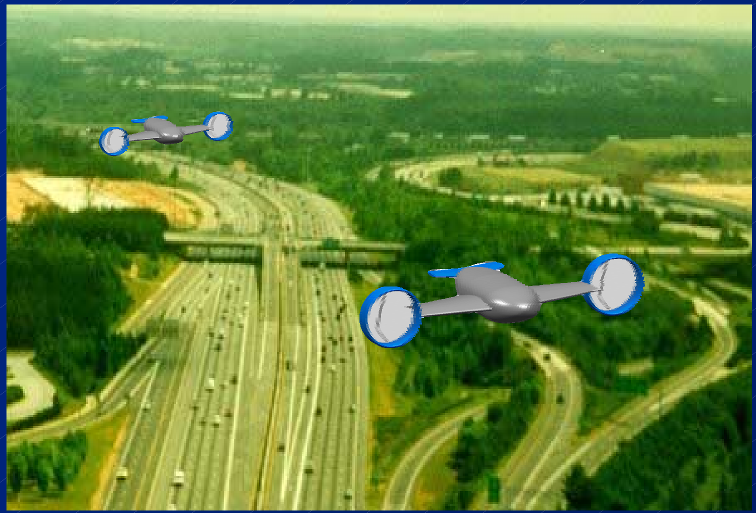
USRA Grant Number 07600-056

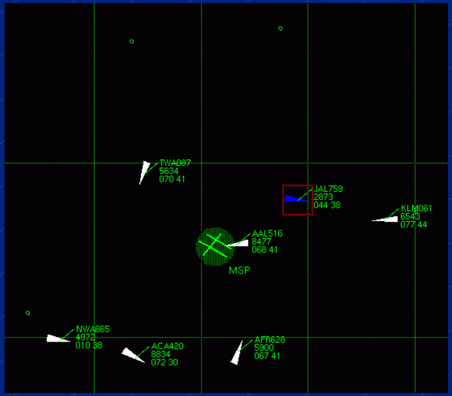
# AVSLA is a Transportation System Solution

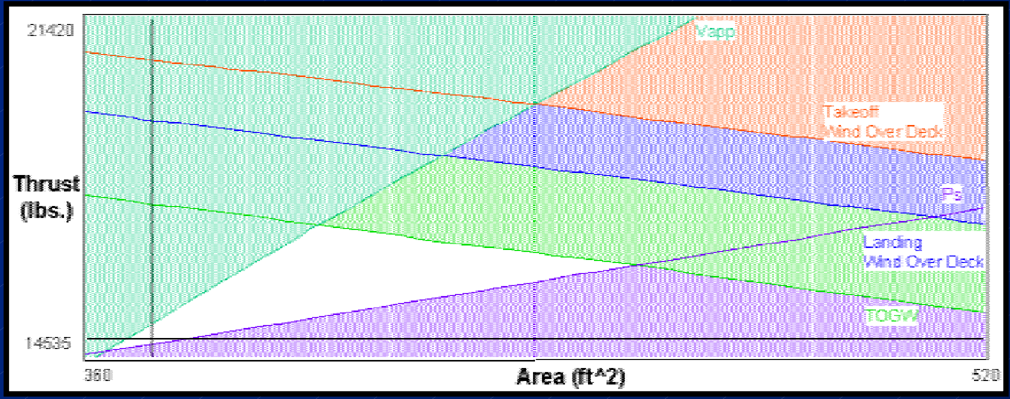
***The Problem***

***The Solution***

# Phase II Team



# What We'll Discuss

- Background
- Phase I Objectives
- Phase I Results
- Phase II Objectives
- Phase II Plan

# Expanding Transportation Capacity is a BIG Problem

**"Despite significant progress, a transportation system that serves a growing America still requires more capacity [and] performance.  The transportation solutions of the past – building more roads, bridges and airports – can no longer be our first choice … It's too expensive and too damaging to our communities and our environment … A total of $39.8 billion is proposed for transportation mobility programs…"**

***from the U.S. Dept. of Transportation FY2000 Budget in Brief**

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# Phase I Performed by Sikorsky Aircraft

- Limited funding for identifying important issues and examining concept feasibility.
  - Contract awarded: May, 2000.
  - Plan presented: June, 2000.
  - Phase I Report delivered: November, 2000.
  - Phase II awarded: May, 2001.
- Phase I results showed promise for concept.
- Phase II benefits from synergistic teaming of Sikorsky and GIT's Aerospace Systems Design Laboratory.

# What’s Next?

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# Phase I Focused on a New Logistics Architecture

- Based on Autonomous air transport.
  - VTOL aircraft provide flexibility and reduce infrastructure investment.
- Broad system focus, not specific technologies/vehicles.
- First pass at determining system feasibility.
  - Economic
  - Technical
  - Socio-political
- Focused on Northeastern U.S. region.

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# 3.6 Million Tons of Cargo Shipped in the Northeastern U.S. Every Day

## Seven Commodities with Value Densities > $10/lb.

| SCTG Code | Description | V/T [$/lb.] | % Total Value Shipped | % Total Tons Shipped |
|---|---|---|---|---|
| 38 | Precision instruments and apparatus | 68 | 3.3 | 0.0 |
| 21 | Pharmaceutical products | 35 | 6.0 | 0.2 |
| 35 | Electronic, electrical equipment/components, office equipment | 29 | 13.2 | 0.4 |
| 9 | Tobacco products | 18 | 0.6 | 0.0 |
| 30 | Textiles, leather, and articles of textiles or leather | 14 | 5.8 | 0.4 |
| 37 | Transportation equipment | 14 | 1.2 | 0.0 |
| 34 | Machinery | 11 | 5.4 | 0.4 |
| **Total** | | | **35.5** | **1.4** |

**There is $2.3 BILLION worth of these goods on the road each day**

**Aircraft will be able to compete in markets with high value densities**

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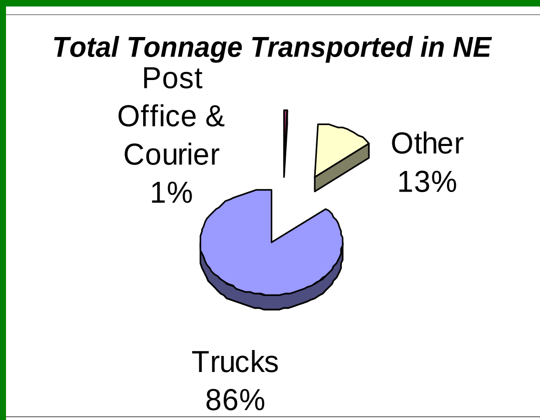
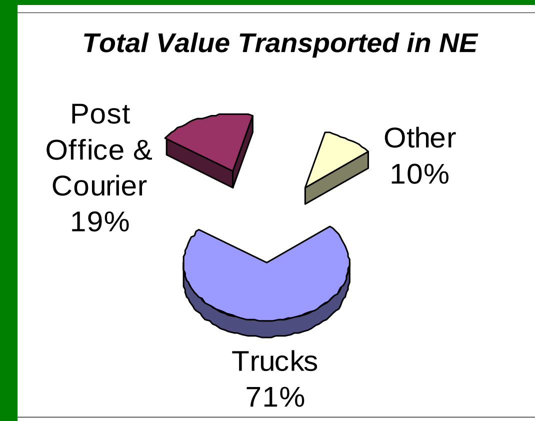
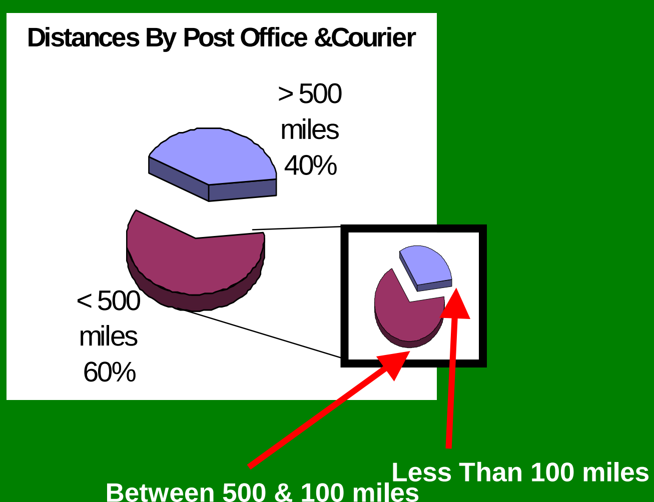
# A Look At The Competition In The NE

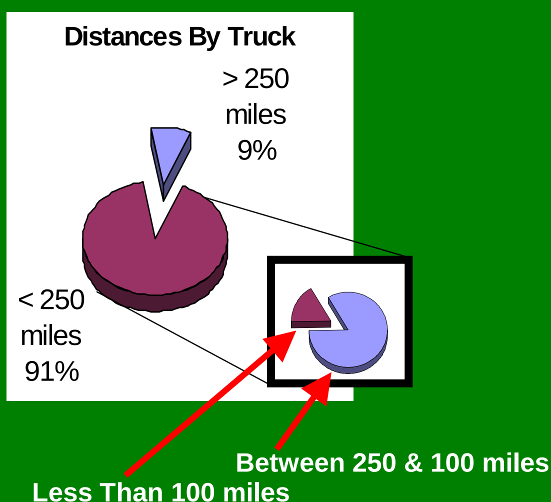



***Fact: 55% Of Truck Deliveries are < 10,000 lb.***

***Fact: 60% Of Postal & Courier Deliveries are < 100 lb.***




- *Light aircraft designed to deliver a 100 lb. payload 500 miles.*
- *Heavy lift aircraft designed to deliver a 10,000 lb. payload 250 miles.*

# The Current Transportation System is Expensive

- Direct Expenses
  - Fuel / parts
  - Labor
  - Capital
  - $125.3B per annum on road and bridge construction. Most pavement costs directly related to damage caused by heavy vehicles.*

***Federal Highway Cost Allocation Study, Final Report*, US Department of Transportation, Federal Highway Administration, 1997**

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# Don’t Forget Indirect Costs

- ~6,400 highway deaths (11% of total) attributed to commercial trucks annually.
- Highway vehicles responsible for 62% of CO emissions, 32% of $NO_x$, and 26% of VOCs.
- $4.2B per annum for tire, oil, and battery disposal.
- Traffic congestion estimated to cost $182B per year.
- Crash costs estimated to be $840B per year.
- Trucks are responsible for ~1/3 of these totals: $340 B

**Sources: EPA and DoT reports.**

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# AVSLA Savings Potential

## *AVSLA System Cost Savings*

| Factor | Total Trucking Costs (Millions $) | (Replace 1.76% of trucks in region) (Millions $) | * Assumed Percentage Of Trucking Costs | AVSLA System Costs (Millions $) |
|---|---|---|---|---|
| Infrastructure | $ 14,114 | $ 248 | 0% | $ - |
| Indirect Costs | | | | |
| Air Pollution | $ 1,868 | $ 33 | 50% | $ 16.4 |
| Greenhouse Gases | $ 2,968 | $ 36 | 25% | $ 9.1 |
| Water | $ 858 | $ 15 | 25% | $ 3.8 |
| Noise | $ 1,209 | $ 21 | 50% | $ 10.6 |
| Waste Disposal | $ 92 | $ 2 | 25% | $ 0.5 |
| Congestion | $ 5,594 | $ 98 | 0% | $ - |
| Crash Costs | $ 16,856 | $ 297 | 0% | $ - |
| ***Total*** | ***$ 42,659*** | ***$ 751*** | | ***$ 40.4*** |

***$710 Million Saved in Northeast alone !***

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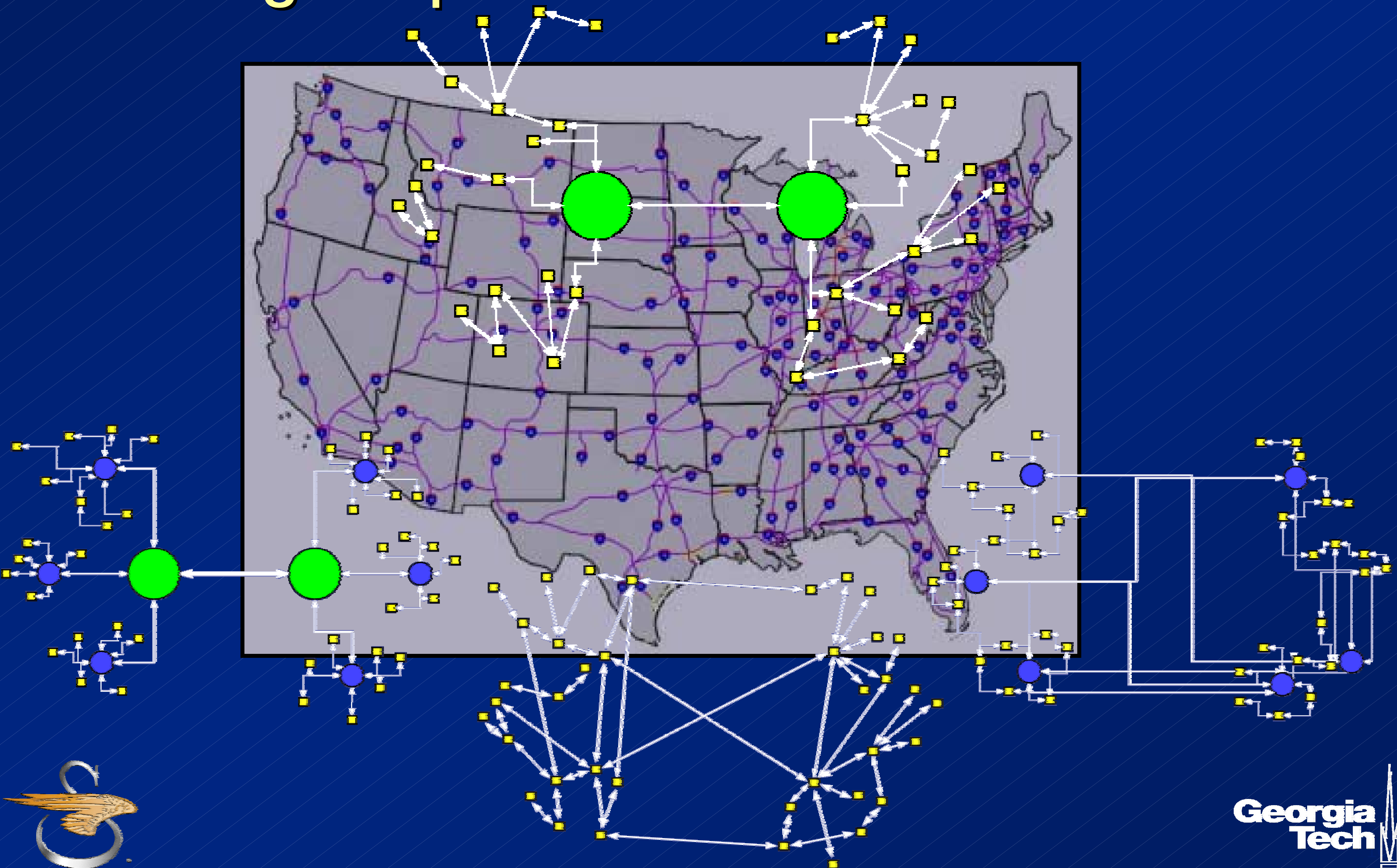
# Delivery Network Topology Design Space



# System Scheduling Design Space

- Scheduled service
  - Follow a pre-determined schedule
  - Analogous to a railroad
- Posture-based service
  - Response based on location of assets
  - Quarterbacks make these kinds of decisions
- Priority-based scheduling
  - Response based on priority of event triggers
  - Think of triage in an emergency room
- Predictive-Adaptive Scheduling
  - Prepare for expected demand, but be flexible
  - Similar to restaurant employee scheduling

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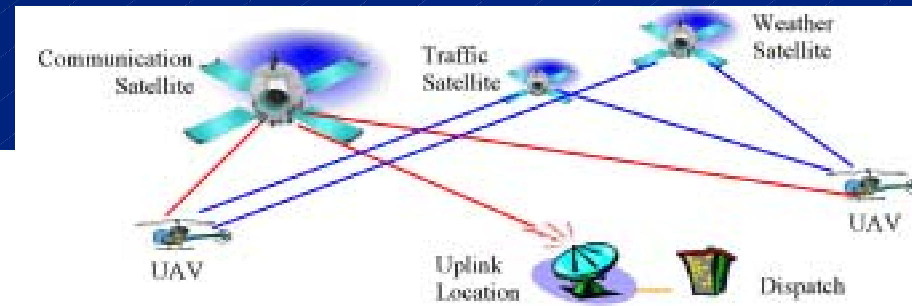
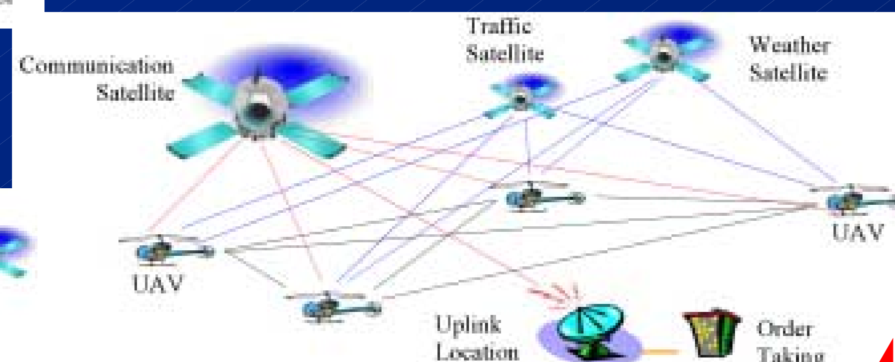
# Control Concept Design Space

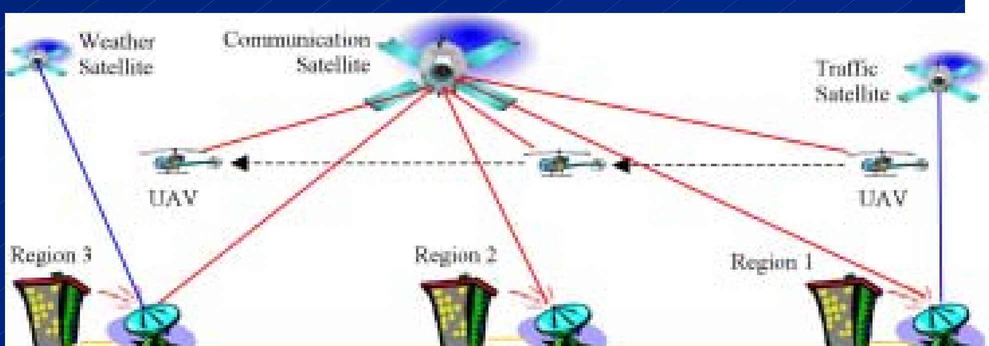



Dispatch Control


Centralized Control




Fully Distributed




Regional Control

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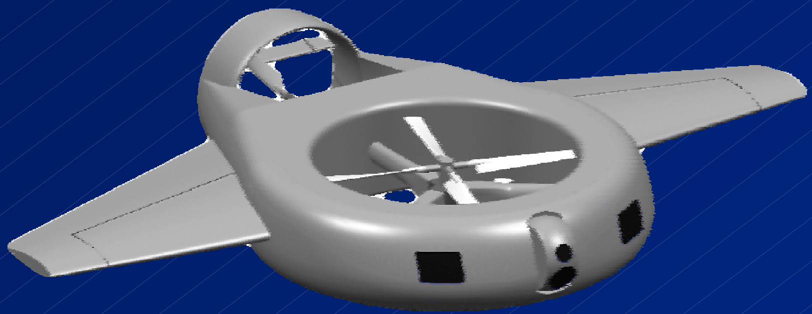
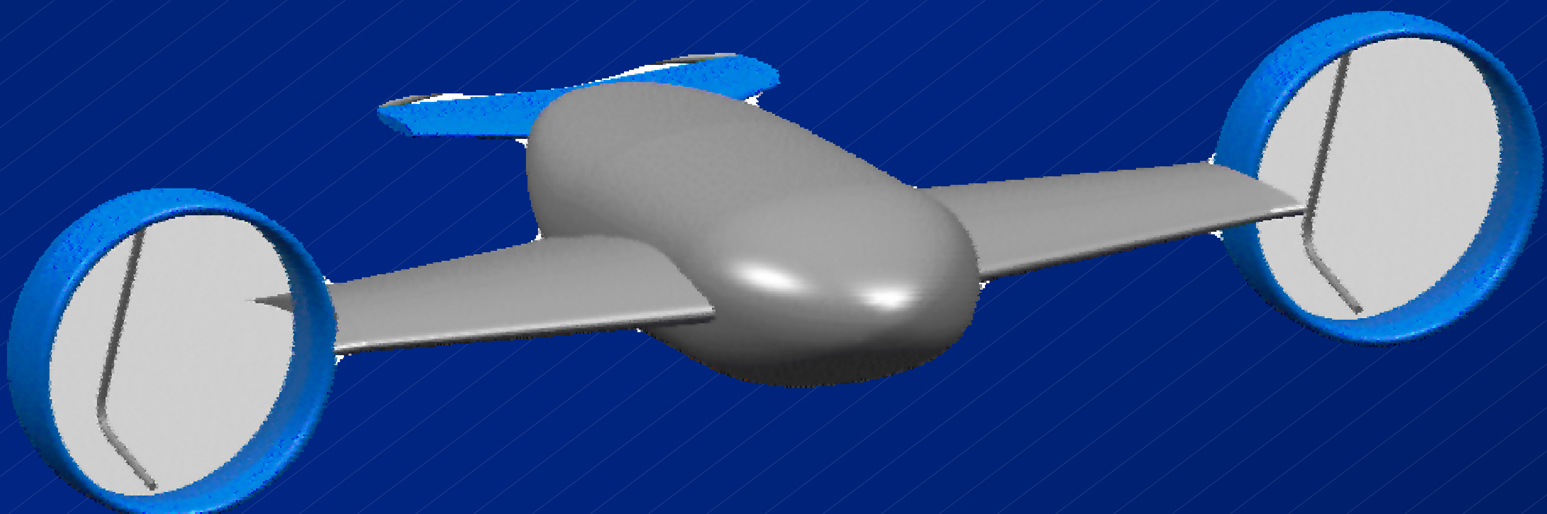
# Light Vehicle Design



**Current Tech:  35 lb. payload, 230 miles, 120 knots**



**Future Tech: 100 lb. payload, 500 miles, ~140 knots**

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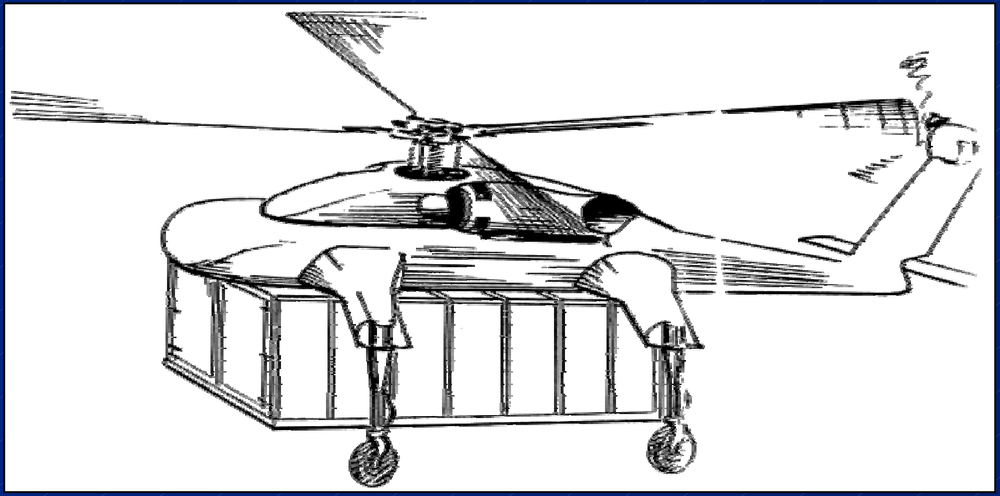
# Heavy Lift Vehicle Design

- Will be studied in Phase II
- Two options for approaching heavy lift:
  - Automate an existing manned helicopter
    - Economies of scale
    - Limited development costs – only developing flight control.
    - Reduced risk



  - Clean sheet design
    - Better performance
    - Tailor fit for customer requirements
    - Expensive

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# Economic Comparison

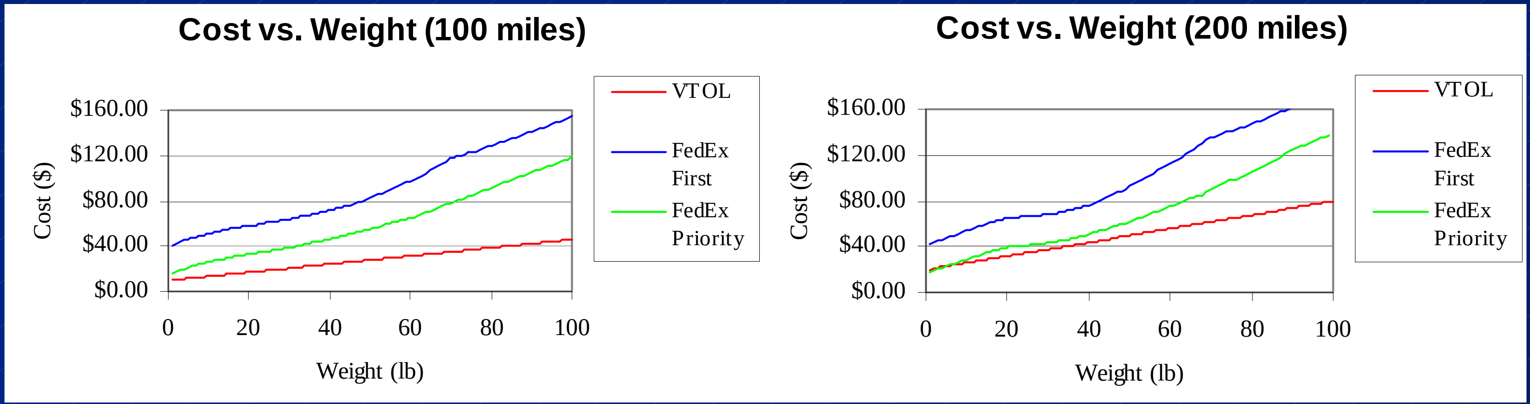
## Capital Costs

| Basic Comparison of Vehicle Cost (Excluding Financing Costs) | | |
|---|---|---|
| | 1-Package VTOL | Current Trucks |
| Packages per Day | 1,500,000 | 1,500,000 |
| Packages per Hour | 187,500 | 187,500 |
| Vehicle Cost (each) | $4,000.00 | $50,000.00 |
| # of Vehicles Needed | 187,500 | 8,600 |
| Total Cost of All Vehicles | $750,000,000.00 | $430,000,000.00 |
| Vehicle Life (years) | 8 | 12 |
| Vehicle Cost per Year | $93,750,000.00 | $35,833,333.33 |
| Vehicle Cost per Day | $360,576.92 | $137,820.51 |
| Vehicle Cost per Package | $0.24 | $0.09 |

## Operational Costs

| | Delivery Van | Light AVSLA | Units |
|---|---|---|---|
| **Fuel** | 0.12 | 0.12 | $/pkg-hr |
| **Misc. Finance Cost** | 1.02 | 1.08 | $/pkg-hr |
| **Maintenance** | 0.19 | 0.25 | $/pkg-hr |
| **Personnel** | 1.40 | 0.43 | $/pkg-hr |
| **Total Operations Cost** | 2.73 | 1.88 | $/pkg-hr |
| **Speed** | 15 | 90 | mph |
| **200-mile delivery time** | 13.33 | 2.22 | hr |
| **Operational cost for 200-mile delivery** | 36.40 | 4.18 | $/pkg |

**Operational savings outweigh capital costs.**



# Phase I Identified Technology Roadmap Issues

- Advanced system will rely on improved information gathering and sharing.
- Communication link integrity and security is a basic requirement.
- Integration with the National Airspace will be a key issue.
- Free flight initiatives will benefit this system.
- It is necessary to both improve the vehicle technologies and reduce life-cycle costs.

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# AVSLA Team- Phase II Goal

***Autonomous VTOL Scalable Logistics Architecture (AVSLA)***

"AVSLA is envisioned to be a future cargo delivery "system-of-systems" that provides cheaper, more efficient, and more effective service to the nation's consumers. Related VTOL vehicles for military heavy-lift purposes are also likely to benefit from AVSLA technology. The stated goal of the NIAC Phase II program is to provide a sound basis for NASA to use in considering advanced concepts for future missions. Thus, this Phase II proposal focuses on specific, critical research areas identified for AVSLA."

**"The overall technical goal is to develop a system-of-systems model of the AVSLA design space, complete with supporting analyses in key areas, that, when combined with advanced probabilistic design methods, can establish a solid basis for establishing a full-scale research program at NASA."**

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# Phase II Partnerships

"Need UPS for realism of cost. It will take UPS involvement to be sure that the numbers are realistic"

- Collaboration established with ***UPS e-ventures*** in Atlanta
- First meeting June 18; attendees include logistics experts as well as business planners

"Working with the FAA at this point is critical; Without buy in by the FAA, any concept of this type is dead on arrival"

- Collaboration with GTRI in Atlanta and FAA in Washington
- **Objectives**: understand regulatory issues & emerging technologies (ADSB, etc), to **leverage planning** for next-generation NAS

US Army

- Contact made with AMCOM (AMRDEC)
  - Emerging Army center of excellence for UAVs
  - Interest in autonomous resupply of Future Combat System

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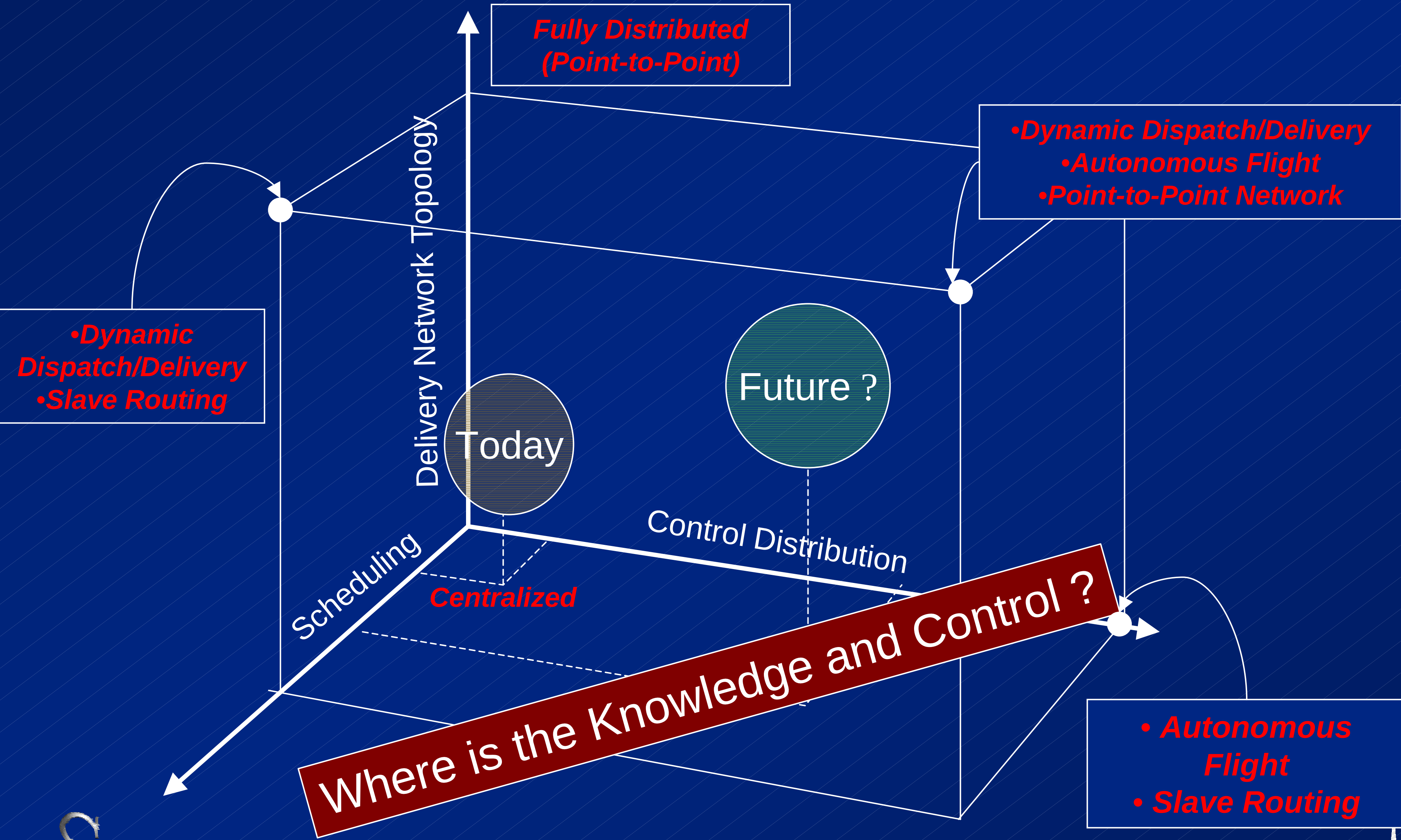
# AVSLA Knowledge-Centric Design Space



# Key Technical Objectives

- **Develop a AVSLA system-of-systems methodology, that creates an infrastructure for continued study:**
  - Expand the system dynamics model to explore **National** (NE + SE) & **Urban** settings
  - Create ability to trade-off different network topologies, control technologies, etc.
  - Create ability to account for "dynamic markets", i.e. answer the question "Is the given AVSLA concept robust to market changes" (Business Plan)

- **Understand technology co-evolution!**
  - Any future delivery architecture will have to **co-evolve** with legacy delivery systems and transportation infrastructure
  - *AVSLA will not magically appear all at once*
  - Understand and model **capital cost and ATC constraints** related to transition
  - Consider the creation of new markets to speed transition (business innovation!)

***FAA/GTRI Partnership***

- **Understand fundamental issues in package delivery**
  - Cost Drivers!- Number of touches, direct operating costs
  - Hub/Spoke Operation; Sorting functions, technologies, bottlenecks
  - "Transition time" costs/implications

***UPS Partnership***

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# Key Sub-Areas of Research

- Onboard vehicle computing (Comm/Nav/FCS)- How much?
  - Finding in Phase I- For the small VTOL, it is critical to determine which capabilities are feasible “on-board” in point-to-point architecture
- Reliability of Autonomous Service/Control
  - Dr. G. Vachtsevanos (GT-EE), Vehicle Autonomy/QoS Expert
- NAS/ATM System Integration
  - Number 1 Issue for AVSLA, from a safety and public acceptance point of view
  - C. Stancil (GTRI) and FAA expertise
- Transportation Architecture Scalability (*up and down*)
  - NE Region modeled in Phase I
  - Do the dynamics change in **national-scale model** (NE+SE) ??
  - Do the dynamics change in **urban setting** ??

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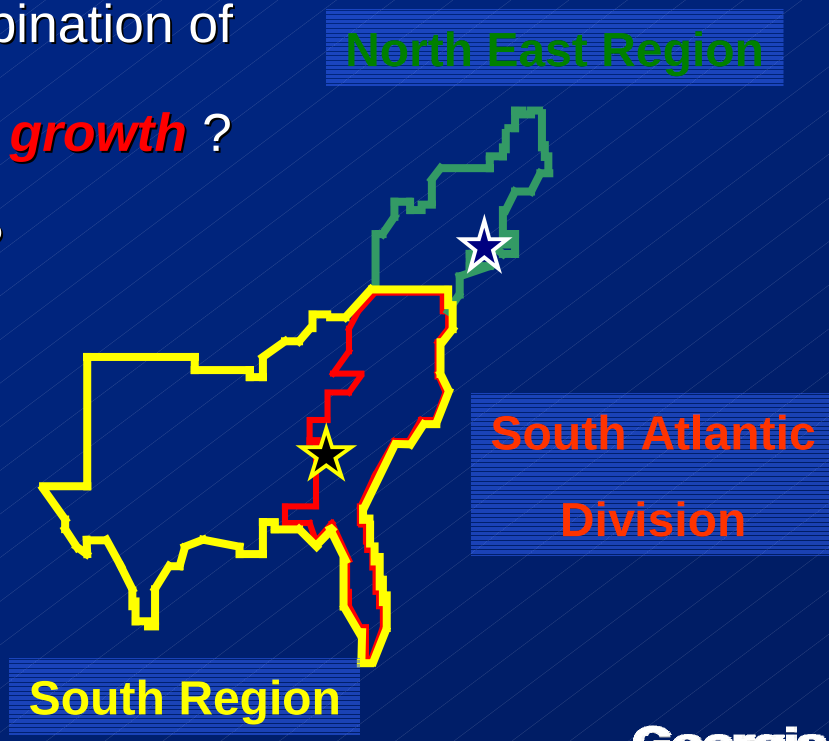
# Exploring The Economy Of The Southeast

- The South Atlantic division of the South region
  - (Delaware, DC, Florida, Georgia, Maryland, N&S Carolina, Virginia, W. Virginia ***9 states***)
- Which commodities offer the best combination of

***value density, market size, and market growth*** ?

- How are these commodities delivered?
- How far are these items shipped?
- How large are the shipments?



# Determining The Ideal Commodities For Delivery…

- Value density, growth, total value combined into a single "goodness" indicator
- Each metric is normalized

$$Value_{A\ (Normalized)} = \frac{Value_A}{\sqrt{Value^2{}_A + \ldots + Value^2{}_Z}}$$

1 - nominal

1.1 - 10% more important

1.2 - 20% more important

| | Total Value | Value Density | Market Growth | |
|---|---|---|---|---|
| | Evaluation Criteria | | | |
| Weight | 1 | 1.2 | 1.1 | |
| Commodity | | | | Score |
| Tobacco | 0.15 | 0.26 | -0.21 | 0.228 |
| Pharmaceuticals | 0.24 | 0.32 | 0.39 | 1.044 |
| Textiles | 0.70 | 0.13 | -0.03 | 0.826 |
| Electronics & Office Eq. | 0.57 | 0.44 | 0.35 | 1.480 |
| Transportation Equipment | 0.08 | 0.38 | 0.01 | 0.543 |
| Precision Equipment | 0.11 | 0.64 | 0.48 | 1.406 |
| Industrial Machinery | 0.29 | 0.24 | 0.63 | 1.268 |
| Furniture | 0.10 | 0.11 | -0.22 | -0.014 |

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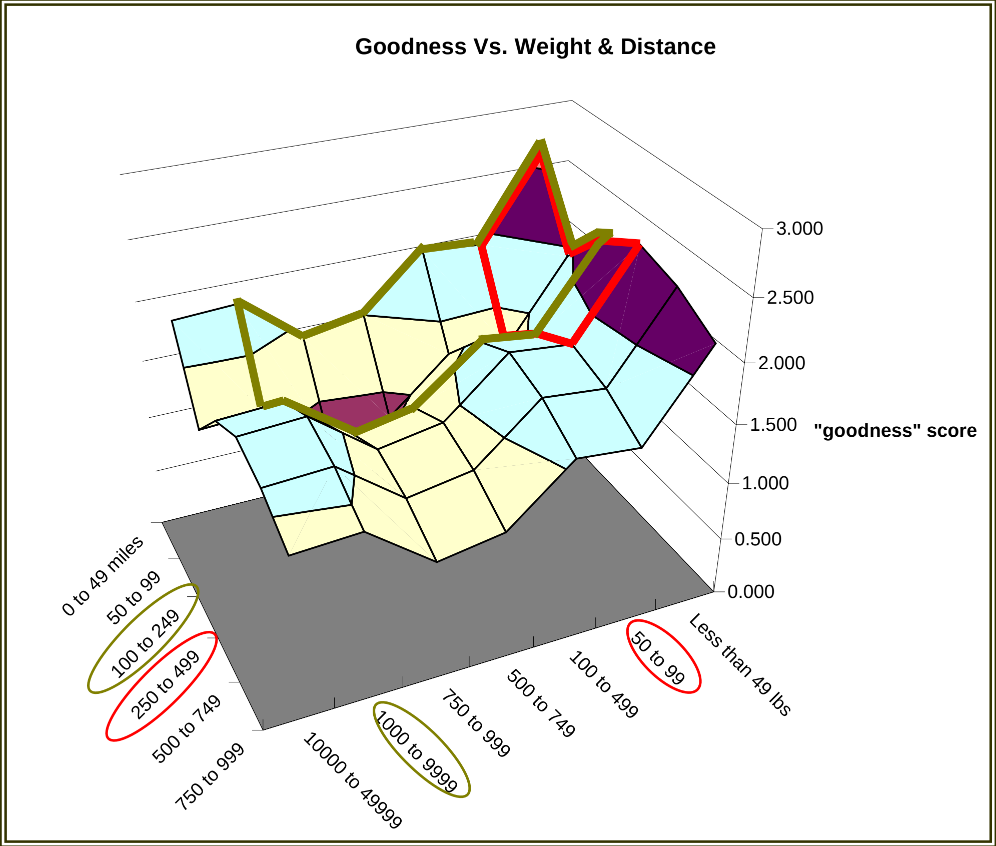
# Determining The Ideal Commodities For Delivery…

- Target Commodities:
  – Pharmaceuticals
  – Industrial Machinery
  – Precision Equipment
  – Electronics & Office Equipment

For The NE, you may recall:

- **Heavy vehicle**
  – 10K lb. payload
  – 250 statute mile range
- **Light vehicle**
  – 100 lb. payload
  – 500 statute mile range

**** Applicability of North East reqm'ts in the South Atlantic Division***




*** Primary Data Source: *1997 Commodity Flow Survey, South Atlantic Division*, U.S. Dept. of Transportation April 2000**

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# Structured Design Methodology Provides Critical Functions

- Ability to explore, compute, and visualize sensitivities of key AVSLA objectives to:
  - Economic and Regulatory requirements
  - Vehicle and Information technologies
  - System architecture variables
- It is critical to quantify and track RISK from the beginning in order to realize the advanced AVSLA concept
  - A credible technology roadmap, including risk, is essential for NASA to consider funding in base R&T
- Design Decision Documentation

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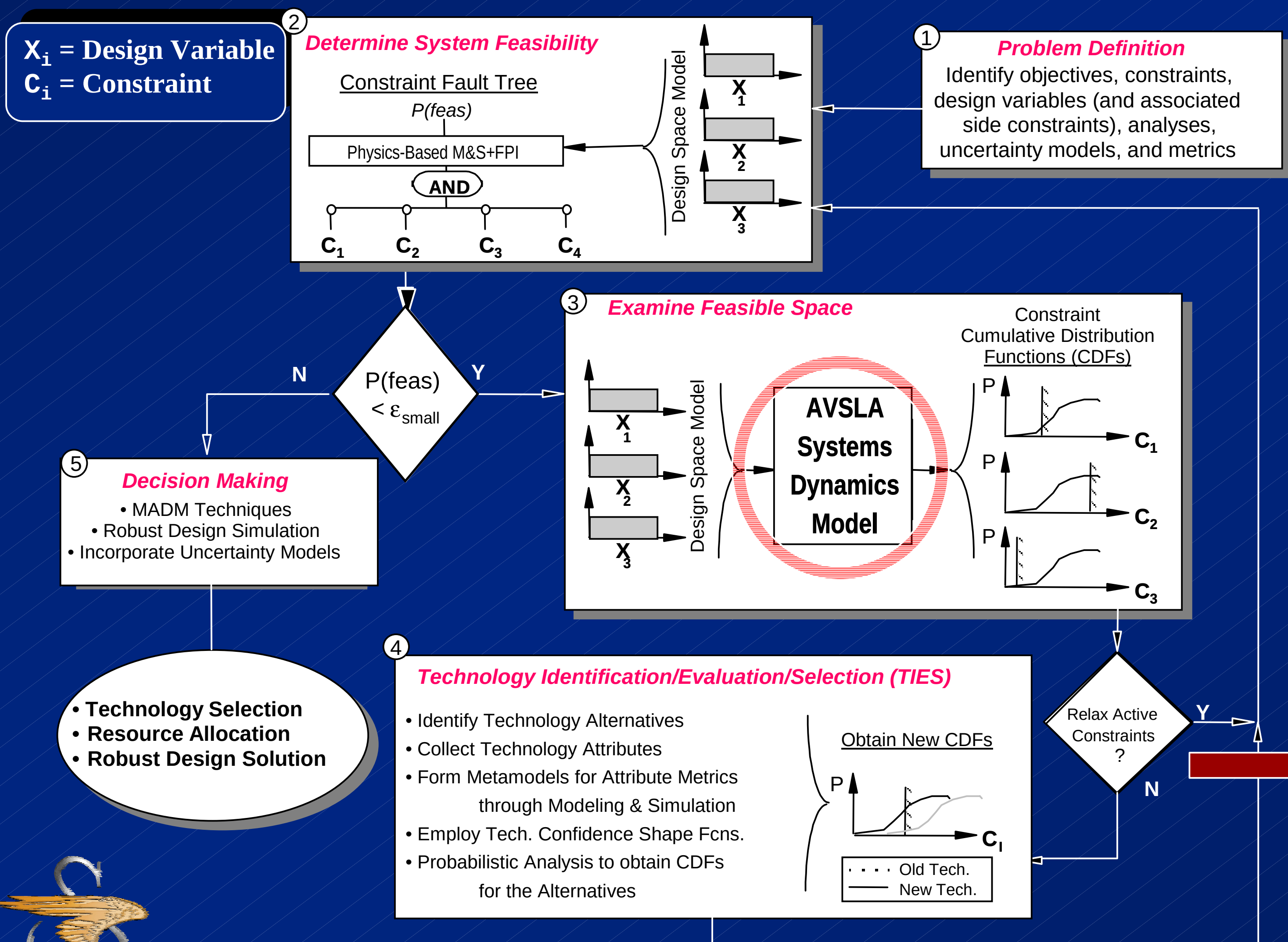
# Methodology for Continuous Design/Development




The "UTE"

It is at this critical decision-box that we need to examine requirements, potential technologies, and concepts

# Concept Alternative Generation

**Example:**

- ***Point-to-Point Topology***
- ***Single Vehicle System***
- ***Docs+Small Parcel***
- ***Express Service***
- ***Auton. VTOL***
- ***50-500 miles***
- ***Real-time pkg track***
- ***……..***

| | | | | | |
|---|---|---|---|---|---|
| Horizontal Delivery System Topology | Hub & Spoke | Point to Point | Hybrid Distributed | Dynamic Network Topology | |
| Vertical Delivery System Topology | Single, All-Purpose Vehicle | Separate Delivery Vehicle and Transfer Vehicle | | | |
| Package Type | Document | Standard Mail | Small Parcel (< 50lbs, < 2x2x2 ft) | Freight (sizes above Small Parcel) | |
| Shipment Time | Same-day (SuperExpress) | Next-Day (Express) | Same-week | Variety | |
| Vehicle Type | Fixed Wing A/C (wide-body Jet or regional turboprop) | Trucks and Vans | Autonomous VTOL-Heavy | Autonomous VTOL-Light | Small Mobile Vehicles (Bicycles, etc) |
| Mission (Range) | Urban ( < 50 miles) | Regional (50 - 500 miles) | National ( > 500 miles) | International | |
| Air Traffic Control | Current ATC | ADS-B | ADS-B (TIS-B, FIS-B) | VTOL Corridors | Free-Flight |
| Operation Control | Autonomous | Semi-Autonomous | Non-Autonomous (Slave) | | |
| Strategic Control (Dispatch) | Centralized | Distributed to Hubs | Distributed to Vehicle | | |
| Package Sorting | Current System | Sort at each stop/hub | | | |
| Package Tracking | No tracking | Update Tracking at each stop | GPS Tracking / per vehicle (real time) | GPS Tracking / per package (real time) | Hand tagging |
| Number of Hand-offs | Two (Pickup,Delivery) | Three (pickup, transfer, delivery) | Four | Five | Six |
| Pick-Up/Delivery Approach | Fixed number of standard "smart" containers | Customer packaging, restricted in size & volume | | | |

**So many possibilities!**

**THOROUGH Ops/Econ Analysis and technology evaluation can reduce the "option space" to some extent**

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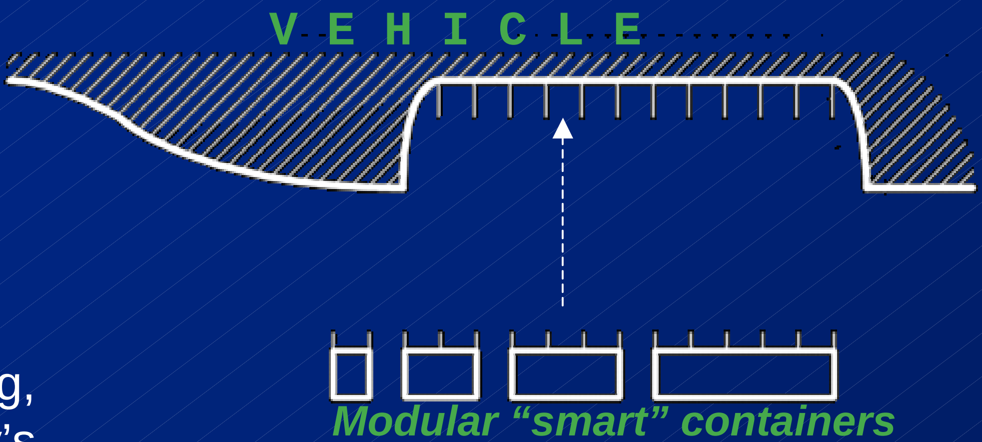
# Many Trades to Be Made-
## *e.g. Modular “Smart” Container?*

*Each Row in the Morphological Matrix represents a set of trade-offs that must be made, including interaction with other rows (systems)*

Example:
Pick-up/Drop-off interface

❶ Option 1 (Right): Modular “smart” containers, accommodating a fixed number of discrete package volumes

❷ Option 2: Customer chooses packaging, places it in “smart box” similar to today’s FedEx boxes, transfer en-masse to vehicle (sorting on-board?)



# Dynamic Visualization of Analyses-
## A Notional “Look Ahead” at AVSLA Candidates

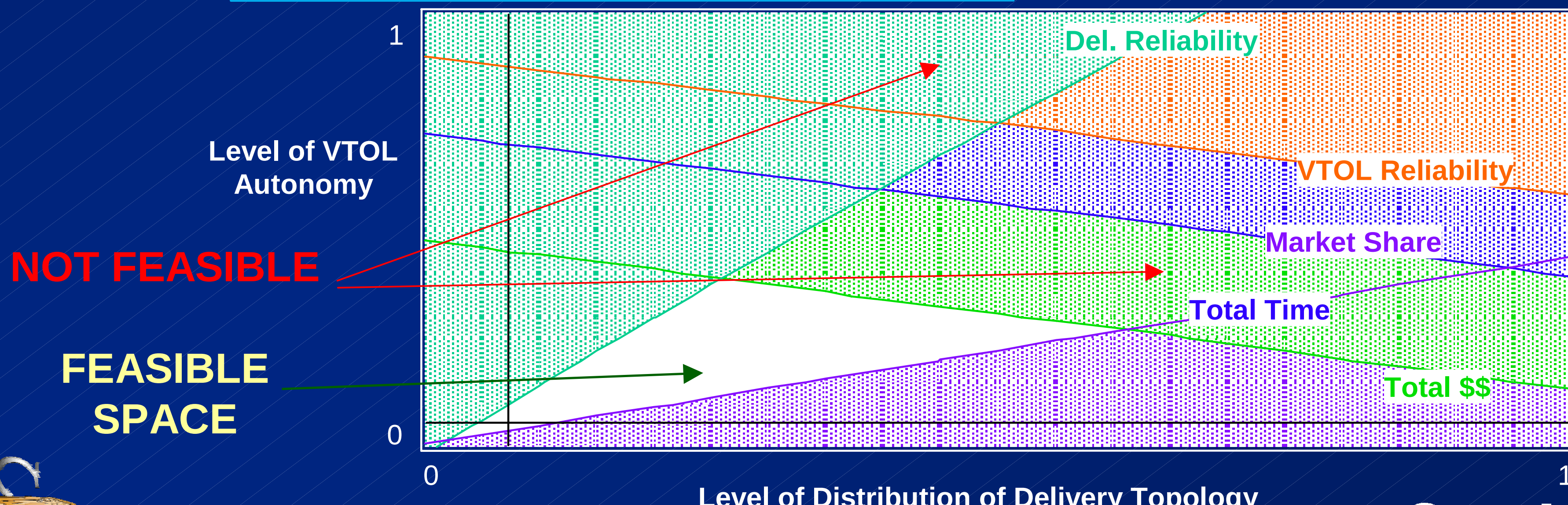
| Horiz | Vert | Factor | Current X |
|---|---|---|---|
| ☐ | ☐ | Delivery Range | -0.8888 |
| ☐ | ☐ | VTOL Comm Tech | 0 |
| ☐ | ☐ | Payload | 0 |
| ☐ | ☐ | Trans Delay Time | -1 |
| ☐ | ☒ | VTOL Autonomy | -0.8888 |
| ☒ | ☐ | Topology Distrib. | -0.857 |

| **Response** | **Current Y** | **Lo Limit** | **Hi Limit** |
|---|---|---|---|
| Total Cost | 37137.19 | ? | 40000 |
| Total Time | 4.812 | ? | 15 |
| VTOL Reliability | 0.87635 | 0.8 | ? |
| Delivery Reliability | 152.42 | 0.7 | ? |
| Market Share | 700.21 | 695 | ? |

INTERACTIVE Slide bars control design variable values

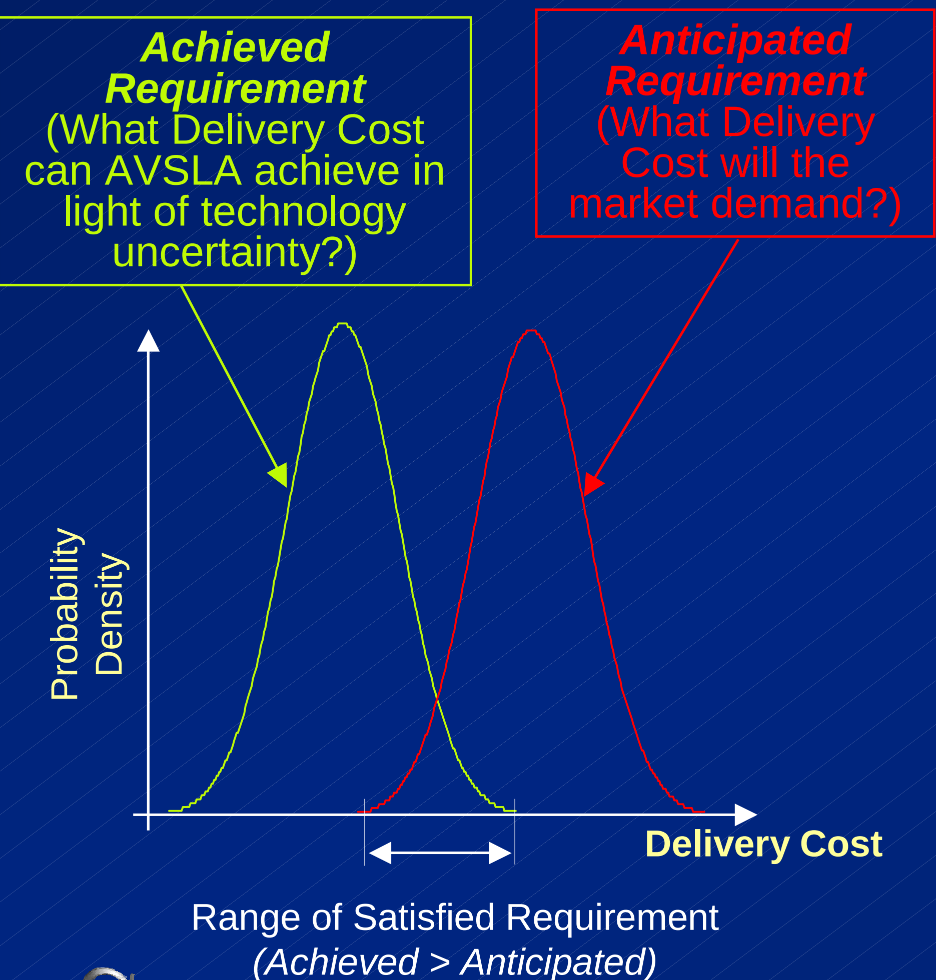
AVSLA Figure of Merit contours set here

Constraints are set here

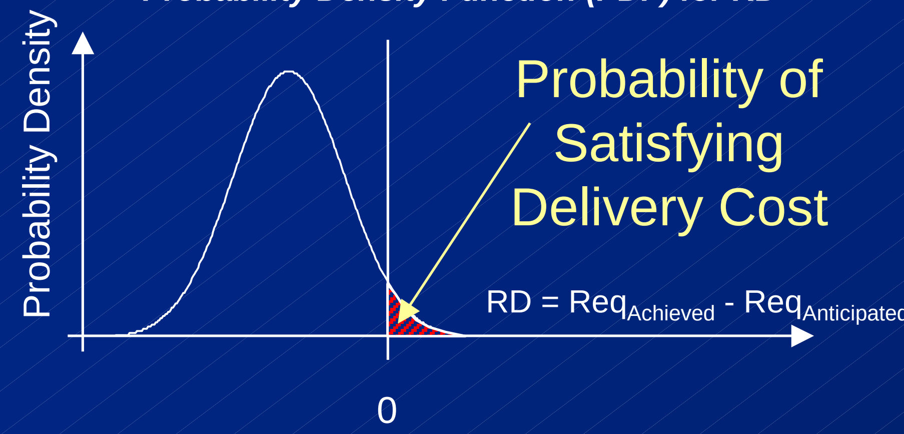


# Requirements Ambiguity + Tech. Uncertainty: *Assessing RISK in AVSLA Development*

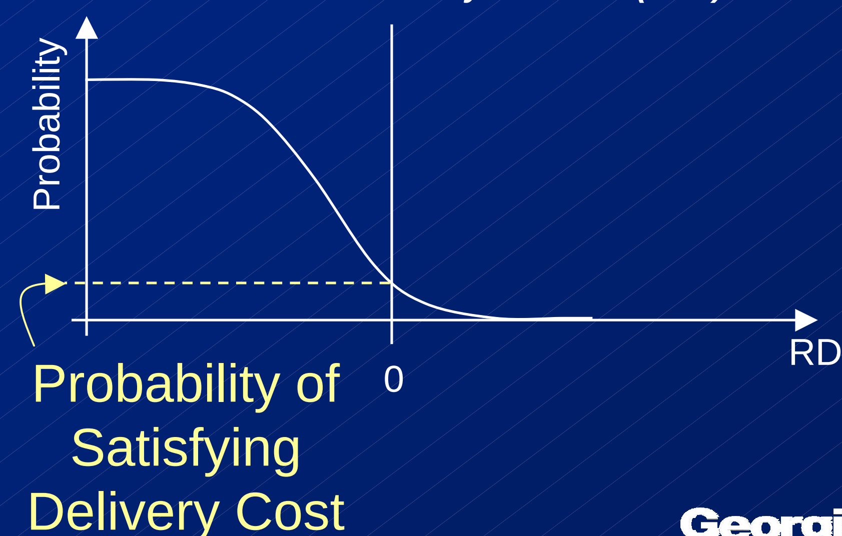
## *One Requirement (1-D) Example*




***Probability Density Function (PDF) for RD***




***Cumulative Probability Function (CDF) for RD***



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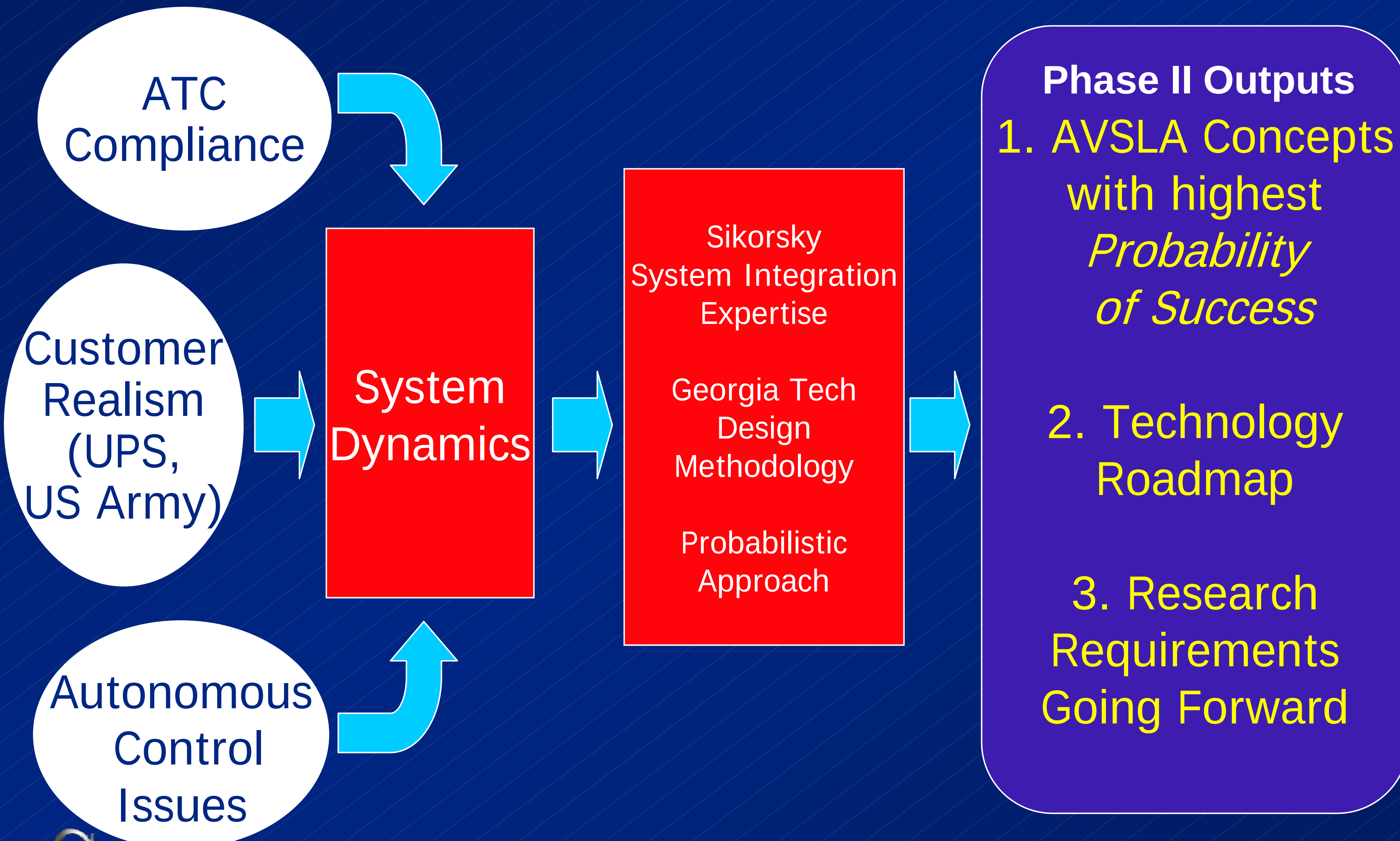
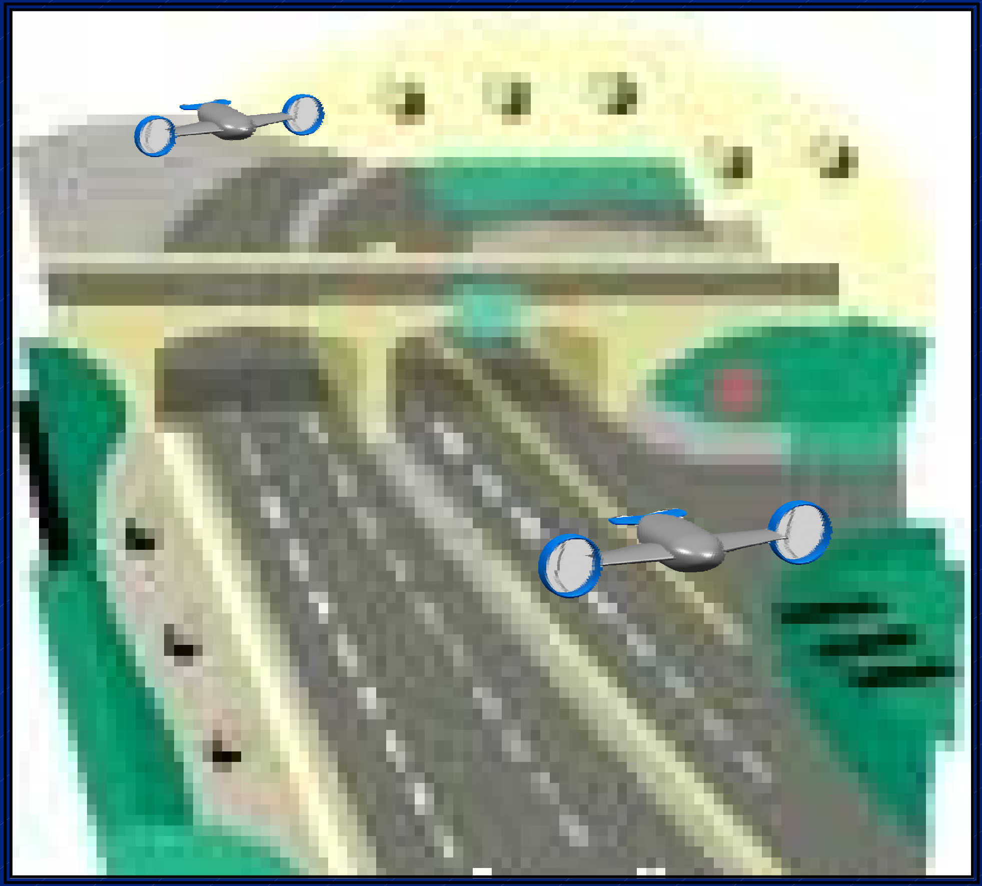
# The Road Ahead



# AVSLA is a Transportation System Solution

***The Solution***



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